ADVANCED RADIOISOTOPE POWER SYSTEM TECHNOLOGY DEVELOPMENT FOR NASA MISSIONS 2011 AND BEYOND (ESA SP-502)

Jack F. Mondt[(1)], Subbaro Surampudi[(2)], Bill J. Nesmith[(3)] and Donald Rapp[(4)]

[(1)] Jet Propulsion Laboratory, MS 277-207, 4800 Oak Grove Dr., Pasadena, CA, 91009 USA, Jack.F.Mondt@jpl.nasa.gov
[(2)] Jet Propulsion Laboratory, MS 277-207, 4800 Oak Grove Dr., Pasadena, CA, 91009 USA, Subbarao.Surampudi@jpl.nasa.gov
[(3)] Jet Propulsion Laboratory, MS 277-207, 4800 Oak Grove Dr., Pasadena, CA, 91009 USA, Bill.J.Nesmith@jpl.nasa.gov
[(4)] Jet Propulsion Laboratory, MS 157-316, 4800 Oak Grove Dr., Pasadena, CA, 91009 USA, Donald.Rapp@jpl.nasa.gov

ABSTRACT

NASA's Office of Space Science requested JPL to lead an assessment of advanced power technologies to enable future NASA Space Science missions. This paper summarizes the result of reviewing the power requirements for future NASA deep space and Mars science missions and providing a technical assessment of candidate advanced radioisotope power system (ARPS) technologies for these missions, including technology road maps. Uncertainties in the lifetime performance of ARPS conversion technologies as well as in the future supply of Pu-238 dictate that several technologies need to be further developed before selecting the optimal one for implementation. It is recommended that the Advanced Stirling Engine Converter (ASEC), Alkali Metal Thermal to Electric Converter (AMTEC) and Segmented Thermoelectric Converter (STEC) technologies be funded with continuation based on yearly detailed technical progress reviews. Selection of an optimum conversion technology would be based on demonstrated technical progress towards meeting NASA's future mission requirements for deep space science missions beyond 2011.

1. INTRODUCTION

All spacecraft require electrical power in order to accomplish their mission. Power is provided either by a photovoltaic (PV) array with batteries or by radioisotope power systems (RPS)s. Over the years the efficiency, specific power and lifetime of PV arrays with batteries have steadily improved. PV arrays with batteries are the power source of choice for most space missions within 2 au of the sun because of their high specific power, efficiency and reliability.

However, there are missions for which PV arrays with batteries are unsatisfactory. These include missions where the solar flux is too low due to large distances from the sun or variable due to eclipses, shadows, dust and changing distances from the sun. Examples include missions to the outer planets, Jupiter and beyond, and missions on Mars that require (a) operation in shadows, (b) extended lifetimes where seasonal variations and settling of dust on PV arrays would be deleterious or (c) where long-term power throughout the 24.66-hour diurnal cycle is essential.

2. OBJECTIVES

The goal of the assessment team was to identify and assess ARPS conversion technologies with the greatest potential to fulfill future deep space science and Mars mission requirements. The specific objectives were to:

- Review NASA needs for advanced radioisotope power systems (ARPS) for future missions.
- Assess the status and potential performance of ARPS technologies.
- Estimate resources required to advance ARPS technologies to NASA TRL 5-6.
- Prepare development road maps for promising technologies.
- Recommend to NASA and DOE investment strategies for developing ARPS technologies.

3. APPROACH

JPL established the following technical assessment team to assess the conversion technologies and accomplish the objectives of this study.

Rao Surampudi, NASA JPL, Chairperson
Bob Carpenter, Orbital Science Corp.
Mohamed El-Genk, University of New Mexico
Lisa Herrera, Department of Energy
Lee Mason, NASA Glenn Research Center
Jack Mondt, NASA JPL
Bill Nesmith, NASA JPL
Donald Rapp, NASA JPL
Robert Wiley, Booz Allen Hamilton

Radioisotope Thermoelectric Generator (RTG) technology has been used on previous NASA missions to outer planets. However, the performance of RTGs is limited. The system efficiency of the state-of-art (SOA) SiGe RTG is 6.5% and the specific power is 4.5 watts/kg. On the other hand, the SOA SiGe RTG has a proven long lifetime > 20 years. The motivations for developing ARPS technologies include the following potential improvements over RTGs:

- Increase the specific power by about a factor of 2 (from 4.5 to 9-10 watts/kg)
- Increase the system efficiency by a factor of 2 to 4 (from 6% to 13%-25%). This reduces the amount of Pu-238 fuel and the cost for any power level.
- Reduce the recurring cost of RPSs
- Reduce the flight RPS fabrication time from project start to delivery to the launch site.
- Retain the long lifetime of RTGs

The ideal ARPS technology is one that accomplishes all of the above.

The team used a scaled-down 100-watt version of the Cassini 285-watt SiGe RTGs as a baseline against which ARPS technologies were compared. The power requirements of most future deep space science and Mars missions can be met with an RPS module that is sized to deliver 100 watts electric at the beginning of mission (BOM). Most missions will likely require several such RPS modules. In this assessment, the team assumed that a RPS uses a specific number of GPHS modules at an assumed BOM thermal power of 240 watts/module. The number of GPHS modules was chosen so that each ARPS technology module BOM power output is 100 watts or slightly greater.

4. CRITERIA

The parameters used to evaluate the advanced technologies are:

1) safety, 2) lifetime and fault tolerance, 3) specific power, 4) conversion efficiency, 5) applicability to a wide range of mission requirements, 6) development risk, 7) spacecraft interface issues, 8) converter-GPHS interface issues, 9) feasibility of validating the lifetime performance for 15-year missions.

NASA Technology Readiness Levels (TRL) was used to describe the status of technologies. TRL 1 and 2 refer to new technologies that are in the early stages of emergence. We are primarily interested in technologies that have already reached TRL 3 where critical functions have been tested on breadboard configuration in a laboratory environment to validate a proof-of-concept's potential performance. The goal is then to assess what program would be required to advance these technologies from NASA TRL 3 to TRL 5.

At NASA TRL 5, a realistic breadboard portion of the system is thoroughly tested in a relevant environment that demonstrates the flight system design. Subsequently, the technology is transferred to a system integrator to develop a flight RPS that meets the requirements of a specific space science mission. NASA-JPL projects require that a technology reach TRL 6 (system engineering model with approximate "form fit and function" of a flight system tested in a relevant environment on ground or in space) by spacecraft Preliminary Design Review (PDR) in order to be selected for use on a NASA primary mission

The ARPS assessment team estimated the resources needed to advance selected candidate ARPS from ~ TRL 3 to TRL 5. A critical element of technology development is assessing the probable lifetime of ARPS. This requires accelerated testing of components, subassemblies and systems to validate lifetime prediction codes. In-depth analysis of failure modes and accelerated tests are required to validate ARPS lifetime performance prior to launch.

5. FUTURE NASA MISSIONS THAT MAY REQUIRE RPSs

NASA Solar System Exploration (SSE) enterprise's future mission concepts beyond 2011 includes Pluto-Kuiper Express, Europa Lander, Titan Explorer and Neptune/Triton Orbiter missions. These missions may have durations of 6 to 15 years missions, and appear to require radioisotope power systems. NASA's Mars Exploration Program (MEP) future mission concepts include Mars surface lander missions every four years beyond 2009. RPSs could provide the longevity and versatility required to accomplish the scientific objectives for these missions. Mission duration is not known but is likely to be in the range 2 to 4 Earth years.

NASA Sun-Earth Connection (SEC) enterprise's future mission concepts include Solar Probe, Interstellar Probe, Interstellar Trailblazer and the Outer Heliosphere Radio Imager missions, each of which requires radioisotope power sources. These missions are in the early stages of planning and the projected power levels are typically 200 to 300 watts with lifetimes up to 30 years.

6. ADVANCED TECHNOLOGIES EVALUATED

Technologies evaluated in this study are listed in Table 1 and described after the table. Advanced Stirling Engine Converter (ASEC), Alkali Metal Thermal to

Electric Converter (AMTEC), Segmented Thermoelectric Converter (STEC), Low Temperature Thermionic (LTI), Thermo-Acoustics (TA) and Thermal PhotoVoltaics (TPV) technologies as applied to ARPS were reviewed and evaluated to satisfy future potential NASA Space Missions. Estimated system masses and efficiencies were made for each technology and compared to a scaled-down design of a 100-watt SiGe RTG.

Table 1. Technologies Evaluated in this Study

Technology	Specific Technology	Comments
Thermoelectric	SiGe RTGs	Used on Voyager, Ulysses, Galileo and Cassini Missions
	PbTe-TAGS	Used on Viking and Pioneer Missions
Stirling Engine Converter	Version 1.0	Present design; efficiency is very good but mass is high; lifetime is not certain; most mature of the ARPS technologies; only one with a reasonable chance of being made ready for Mars 2007
	Version 1.1	Advanced Technology Low Mass Alternator
Advanced Stirling Engine Converter	Version 2.0 or Thermo-acoustic	Low Mass Stirling Engine, alternator, radiator and controller potential for high efficiency long life Stirling Engine. Considered as an advanced form of Stirling Technology.
AMTEC	Refractory Metal Chimney	Potential for low mass and medium efficiency. Being developed by NASA and DOE under existing DOE contract
Segmented Thermoelectric	Advanced Materials/ Segmented Unicouple	Potential for low mass and medium efficiency. Solid state device Radioisotope Power System configuration, operations and handling similar to SiGe RTG
Thermionic	Cesiated triode	Low Temperature 1300K Thermionic early stage of technology development
	Micro-miniature	Early stage of research
Thermo-photovoltaic	Thermal PhotoVoltaic Converter	Early stage of research

The Advanced Stirling Engine Converter (ASEC)-ARPS technology development approach uses a reciprocating free-piston Stirling heat engine (Version 1.1) or a Thermo-Acoustic heat engine with a linear alternator (Version 2.0) that are low-mass versions of the Stirling engine alternator now under development (Version 1.0) by DOE and NASA. The ASEC-ARPS has the principal advantage of increased conversion efficiency to almost four times the system efficiency of the SOA SiGe RTG. Advanced versions of the Stirling engine converter ARPS may have the potential to double the specific power over the SOA SiGe RTG.

The ASEC-ARPS major technical challenges are:

1) Validating the system lifetime for ~15-year missions.
2) Developing an efficient, low mass, long life ASEC-ARPS.
3) Reducing the residual EMI for space missions that measure very small magnetic fields.
4) Reducing the Stirling engine alternator vibration for very sensitive seismic instruments.

The Alkali Metal Thermal to Electric Converter (AMTEC)-ARPS produces electric power by the flow of sodium ions through a Beta-Alumina Solid Electrolyte (BASE) that produces DC current and voltage. AMTEC delivers DC power with no vibration and very small EMI. AMTEC is a young technology with potential system efficiency as high as 20%, which is three times the system efficiency of the SOA SiGe RTG. AMTEC ARPS has the potential for doubling the specific power over the SOA SiGe RTG to 9 watts/kg. The AMTEC-ARPS major technical challenges are:

1) Developing a BASE to metal ceramic seal.
2) Developing a converter refractory metal containment material fabrication process.
3) Developing a reproducible wick-evaporator fabrication process.
4) Developing an electrical feed-through fabrication process.

Segmented-Thermoelectric Converter (STEC)-ARPS contains thermoelectric materials that produce a current and a voltage when placed in a temperature gradient. Each thermoelectric material, whether n-type or p-type, exhibits a maximum figure-of-merit at some temperature. If a single material is used in each leg of the unicouple, the effective efficiency will be an average over the temperature range, which is less than the maximum possible. If each leg of the unicouple is segmented so that a thermal gradient is established down the leg, the temperature gradient over each segment will be relatively smaller. Thermoelectric materials developed with a high efficiency over the small thermal gradient for each segment will achieve a higher efficiency over the entire thermal gradient. The STEC-ARPS has the potential to double the efficiency of the SiGe RTG.

The STEC-ARPS major technical challenges are:

1) Developing a compatible high temperature (973K to 1273K) thermoelectric material.
2) Developing joints between the segments with very small thermal and electric resistance.
3) Developing barriers that prevent inter-diffusion between segments.
4) Developing joints between the high temperature thermoelectric materials and a hot shoe.

7. TECHNOLOGY ASSESSMENTS

The team assessments of these advanced converter technologies for ARPS are as follows:

ASEC-ARPS is likely to quadruple the conversion efficiency over the SOA SiGe RTG. Advanced ASEC-ARPS systems may have the potential to double the specific power over the SOA SiGe RTG. A method to accelerate and validate the lifetime of ASEC-ARPS needs to be developed. Thermo-Acoustic Stirling engine technology may offer less vibration and longer lifetime over conventional Stirling engines but it is at an early stage of development.

AMTEC-ARPS has the potential to double the specific power and efficiency over the SOA SiGe RTG. The lifetime of AMTEC ARPS basic conversion components (BASE, Electrodes and current collectors) have demonstrated >20 years. It is planned that accelerated testing will validate the lifetime performance of components, converter and system. There are no EMI or vibration problems.

STEC-ARPS has the potential to double the specific power and efficiency over the SOA SiGe RTG. STEC-ARPS converters are amenable to accelerated lifetime testing as they are being developed. There are no EMI or vibration problems.

Low Temperature Thermionics and Thermal PhotoVoltaics technologies are at NASA TRL 1-2. There were not enough data for the team to assess the efficiency, specific mass or lifetime for an ARPS for these conversion technologies. The team recommends that some combination of NASA's cross-cutting technology program; the DOE PRDA program; SBIRS and STTRs fund these two technologies to NASA TRL 3 so a realistic estimate of system mass, efficiency and lifetime can be prepared.

Table 2 summarizes the major characteristics, provides estimated system data and compares the team selected candidate technologies, ASEC, AMTEC and STEC to the SOA SiGe RTG. Thermo-Acoustic technology is

Table 2. Characteristics of Candidate ARPS Technologies

Tech-nology	NASA TRL	BOM Watts	Syst Mass kg	Spec Pwr W/kg	Syst Eff. %	GPHS (d)	$M to reach TRL 5	Risk	Life Issues	S/C I/F Issues (e)	Resiliency to Partial Failure
Small SiGe RTG (a)	8	139	31.2	4.5	6.5%	9	None	None	None	None	Highly modular
Stirling 1.0 (b)	4	110	27	4.1	23%	2	$4.5M 2yr	Low	Engine & Control Electronics	AC/DC Control electrnics	Failure of 1 converter may lead to generator failure
Stirling 1.1	4	120	20	6.0	25%	2	$8M 3yr	Med	Helium leakage	Radiator Vib, EMI	
Stirling 2.0	2	120	16	7.5	25%	2	$13.5M 6yr	High	(same)	(same)	(same)
AMTEC (LMA) (c)	3	139	25	5.6	14.5 %	4			Seals, wick, evaporator Contain-ment, matls, fab process	Launch vehicle acceler-ation	Failure of converter results in generator partial power loss
AMTEC Chimney	3	120	13.6	8.8	16.7 %	3	$15M 6yr	High			
Segmented TE (Low T)	2	125	14	8.9	13%	4			Joint bonds, barriers	None	Highly modular
Segmented TE (High T)	2	144	14	10.2	15%	4	$13.5M 6yr	High	New matl Joint bonds Barriers	None	Highly modular

(a) LMA 9 GPHS Vacuum RTG for Europa Orbiter 04 or 05 launch
(b) LMA Stirling RPS study concept for Europa Orbiter
(c) LMA AMTEC preliminary design for Europa Orbiter
(d) Each GPHS module assumed at 240 thermal watts at BOM
(e) Potential spacecraft interface issues with some mission

considered as part of the advanced Stirling technology. In each case, a GPHS module delivers 240 watts thermal at BOM and the number of GPHS modules was chosen to make the BOM power 100 watts electric or greater.

8. RESULTS AND RECOMMENDATIONS

The assessment team recommends that ASEC, AMTEC and STEC technologies be funded and developed by NASA in accordance with a technology plan that includes technology readiness gates for each technology. The progress towards meeting these technologies readiness gates for each technology should be reviewed yearly by the same independent Formal Review Board. Two of these technologies would be selected two or three years after inception of the program, based on the progress made in meeting their technology gates and meeting the requirements for the greatest number of future NASA ESS, SEC and MEP missions. The two selected technologies would then be developed to TRL 5 under a joint NASA/DOE technology program. When the technologies reach NASA TRL 5, a NASA flight project and DOE would jointly select and develop the technology that best satisfies the requirements of that project's specific mission.

A top-level recommended ARPS technology roadmap is shown in Figure 1. This roadmap assumes that NASA and DOE would develop a near term Stirling RPS and/or a 100-watt class RTG, either SiGe or PbTe/TAGS), for potential NASA deep space and Mars science missions that are launched prior to 2011.

9. ACKNOWLEDGMENTS

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10.REFERENCE

Surampudi, Rao, et al, Advanced Radioisotope Power System (ARPS) Team 2001Technology Assessment and Recommended Roadmap For Potential NASA Deep Space Missions Beyond 2011, JPL Report, JPL D-20757, March, 2001.

Funds	Technology	FY02	FY03	FY04	FY05	FY06	FY08
MEP Funds	**Stirling 1.0**	TRL 4 Mtls Charact $3.5M	Life Testing $1.0M TRL 5	System Integration	Flight Development Funding		
	Stirling 1.1	TDC Mod Plan $0.5M	TRL 4 Lt Wt Alt/Cntrl $3.5M	Demo &Test $4.0M TRL 5	System Integration		
Advanced Technology Funds	**Stirling 2.0**	Concept Feasibility $0.5M	Advanced Concepts RFP $2.0M TRL 3	Lt Wt Conv Rad, Cntrl $2.0M	Conv, Rad, Cntrl, Brdbds $3.0M TRL 4	Engrg Model Life Tests $3.0M	Engrg Model Life Tests $3.0M TRL 5
	Thermoacoustics NRA	($650K)	($650K)				
	AMTEC	Mtls devel Chimney Cell $2.0M	Chimney cell, Life validation $2.0M TRL 3	Reproducible cell, Life prediction $2.0M	Integrate 4 converters demo $4.0M TRL 4	Engrg Model Life Tests $3.0M	Engrg Model Life Tests $3.0M TRL 5
	Segmented TE	Mtls eval. $0.5M	Bond/barrier Unicouple fab $2.0M TRL 3	!000K unicouple demo $2.0M	4-cple module accel life test $3.0M TRL 4	18-cple engr models $3.0M	18-cple engr models $3.0M TRL 5
	Segmented TE NRA	(350K)	(350K)	(350K)			
	New Tech $/FY	**$3.0M**	**$6.0M**	**$6.0M**	**$10.0M**	**$9.0M**	**$9.0M**

Notes: Stirling 1.0 & 1.1, System Integration & Flight Development costs, DOE & Mars Funds & CETDP costs not included in totals
Independent Review Board evaluates technology progress at TRL 3,4 &5 to determine to proceed or not.

Figure 1. RECOMMENDED ARPS TEHNOLOGY ROADMAP